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THE

JOURNAL OF GEOLOGY

MAY-JUNE, 1905

THE TWIN LAKES GLACIATED AREA, COLORADO[1]

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OUTLINE

PREGLACIAL TOPOGRAPHY OF THE UPPER ARKANSAS.
GLACIAL FEATURES OF THE TWIN LAKES REGION.
  I. Morainic System of Lake Glacier.
  II. Pleistocene History of the Upper Arkansas.
  III. Glacial Erosion.
POSTGLACIAL CHANGES.
MOUNTAIN FORM.

The Upper Arkansas occupies a broad north-and-south valley between the Park Range on the east and the Sawatch Range on the west. Twin Lakes are on the lower course of Lake Creek, which heads in the Sawatch and flows east to the Arkansas. The lakes are held back by two small recessional moraines deposited by the glacier which formerly occupied the valley of Lake Creek. This paper describes the topographic features of the basin of Lake Creek and of the neighboring part of the Arkansas valley, and treats of the preglacial topography of the region, the topographic effects produced by Pleistocene glaciation, and postglacial changes.

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[1] The writer, on returning from the Harvard excursion to the Great Basin in 1904, spent several weeks in the valley of Lake Creek. Together with Professor W. M. Davis, he had stopped here for a few days earlier in the summer, and he wishes to express his indebtedness to Professor Davis for pointing out the district to his attention as deserving study for its glacial features, and for suggestions in the field and later.

The only early detailed report on the region is found in the *Annual Reports* of the Hayden Survey for 1869, 1873, and 1874. A paper by Capps and Leffingwell, which was published in the *Journal of Geology* for November–December, 1904, discusses the glacial geology of the upper Arkansas valley, and with the conclusions of these writers the author is in substantial agreement, in so far as the two papers deal with the same area. Professor Davis, in *Appalachia*, November, 1904, uses the valley of Lake Creek to illustrate glacial erosion.

PREGLACIAL TOPOGRAPHY OF THE UPPER ARKANSAS

All of the larger tributary valleys of the Arkansas on the west, and some of those about Leadville on the east, were occupied by valley glaciers during Pleistocene time, while the other tributary valleys and the main valley were free of ice. It is thus possible to compare the glaciated and non-glaciated areas, and to determine what features are due to stream-erosion in preglacial time, and to contrast that topography with that which has been changed by glacial action.

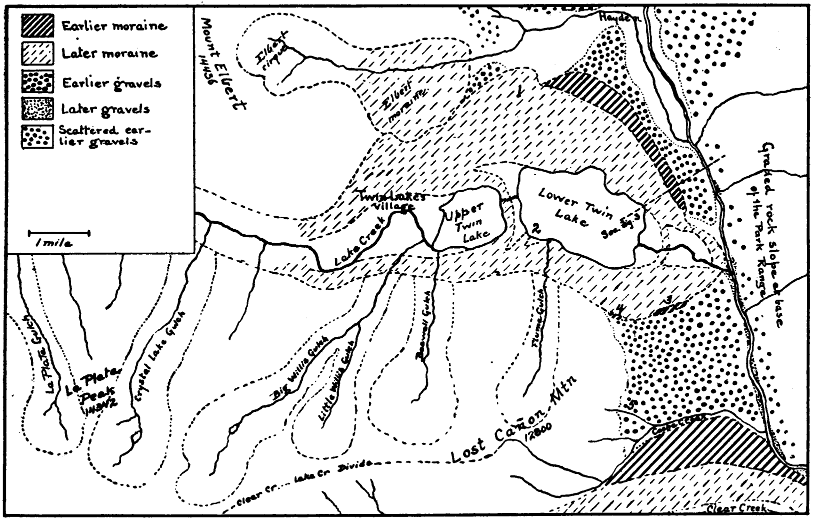

FIG. 1.—Map of the Twin Lakes area.

Fig. 2 will make clear the main elements of preglacial form along the Arkansas. The river flows in a narrow interglacial valley cut 300 to 400 feet into the granite. From the edge of this inner valley on the east a terrace (*BC*), from one-half to a mile in width, rises at an angle of 5° to the foothills of the Park Range. This terrace is cut in granite, and while now somewhat dissected, is evidently a part of the graded rock-floor of the preglacial Arkansas. The west wall of the narrow valley is granite, but the plain (*AD*) stretching west from its upper edge is glacial wash, and not cut on the rock. The rock-plain which one naturally looks for to match that on the east is buried under this wash and is shown at only one point along the base of the range, just south of the south Lake Creek moraine, where placer mining has removed the thin cover of gravel over a considerable area, and shows a graded slope of weathered granite inclining to the east, and at the same level as the back of the corresponding rock-slope east of the Arkansas. Placer digging west of Granite, and occasional shafts, show that the gravel is upwards of 50 to 75 feet in thickness; it may be much more. This gravel filling is probably not thick enough to carry the bottom of the broad preglacial valley, which ran west of the present river, down to the present level of the Arkansas. The dotted line in the section restores approximately the surface of the preglacial valley.

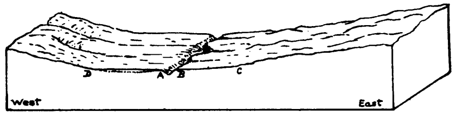

FIG. 2.—Section across the Arkansas River north of Granite.

Horizontal and vertical scale 1 inch =4 miles (nearly).

At its back edge the graded rock-slope passes into the foothills of the Park and Sawatch ranges. The hillsides comprising these ranges are not steep, rarely over 20°, and have graded slopes, without prominent outcropping ledges, and this type of hill form is kept all the way to the summits. These rise some 3,000 to 5,000 feet above the valley, and are rounded and massive. Sharpened summits occur only in the glaciated areas. The Sawatch Range above Granite, Lost Canyon Mountain, and Mount Elbert all show this massive form, which may be taken as the typical preglacial form.

GLACIAL FEATURES OF THE TWIN LAKES REGION

That part of the Lake Glacier (name shortened from Lake Creek Glacier) which lay in the broad valley of the Arkansas was characterized by morainic deposition; that part above Twin Lakes village, and which lay in the narrow valley in the Sawatch, by glacial erosion.

I. MORAINIC SYSTEM OF LAKE GLACIER

1. *Two periods of glaciation.*—The moraines of the Lake Glacier form a rough semi-circle on the west side of the Arkansas, reaching almost to the present Arkansas River.[1] Within this area moraines of two distinct dates are found, separated by a time interval of sufficient length to constitute two separate glacial periods. Their distribution is shown on the accompanying map (Fig. 1). The later drift forms a continuous moraine about the lakes. The earlier drift occurs outside the later drift for four miles north of Lake Creek, and at one or two isolated points south. The evidence for the different age of the two moraines lies (A) in the relations which they hold to the gravels of the Arkansas valley, (B) in the difference in weathering in the two moraines and gravel-plains, and (C) in differences of topographic expression and amount of stream-dissection of the two moraines and their correlated gravels.

A. Relation of moraines to gravels. Two series of gravels occur along the Arkansas. One is a succession of terrace fragments, lying within the interglacial gorge of the Arkansas and rising some 30 to 40 feet above the river. At Lake Creek this terrace rises somewhat steeply to the front of the later moraine, and the relations of the two show clearly that the gravel is a wash-plain formed by the glacial waters contemporaneously with the accumulation of the moraine. The later moraine is therefore of later date than the cutting of the rock-gorge of the Arkansas.

A second series of gravels occurs up to 400 feet above the river-level, back from the upper edge of the rock-gorge, and on both sides of the river. East of the river they form in places a thin veneer over the graded rock-plain of the preglacial Arkansas; in large part, however, they are represented only by scattered bowlders.[2] West of the river they form extensive terraces. That the deposits were originally continuous is shown by their occurrence at the same levels on both sides of the river, and by the fact that the gravel east of the river contains material recognizable as derived from the valley of Lake Creek, and not found east of the Arkansas. Through this sheet of gravel the Arkansas cut its valley, and then 300 to 400 feet into the rock. These higher gravels are therefore older than the rock-valley. But it is with this older series of gravels that the outer moraine is to be correlated. Fig. 3 shows the relations that hold along the whole stretch of the old moraine north of the river. *A* is the later moraine; *B*, the earlier moraine; *C*, the upper gravel-terrace. On the rock-terrace at *D*, scattered bowlders or thin gravel veneer mark the former eastward extension of the terrace. *E* is the gorge gravel of younger date. *C* is the wash-plain to the outer moraine *B*, just as

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[1] There is no evidence that the Upper Arkansas was ever occupied by a north-and-south master-glacier, as suggested by Hayden, *Annual Report* for 1873, p. 48.

[2] Referred to by Capps and Leffingwell (*Journal of Geology*, Vol. XII, p. 702) as possibly indicating a third period of glaciation earlier than the two to be mentioned later. They seem to be associated, however, with the upper terrace gravels, though floating ice may have had some share in bringing them to their present condition, as they are sometimes 2 to 3 feet in diameter.

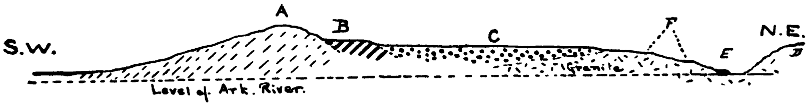

FIG. 3.—Profile from lower Twin Lake northeast to the Arkansas. Symbols as in Fig. 1.
Horizontal scale, 1 inch=2,000 feet; vertical scale, 1 inch=5,000 feet. The section is located on the map.

the gorge gravels are to the later moraine. These relations of the moraines to the gravels show that the periods of ice-advance indicated by the two moraines are separated from each other by a time interval sufficient for the Arkansas to cut its gorge 300 to 400 feet below the floor of its broad, graded, preglacial valley. When one compares the work done in this period with that done by the river in postglacial time, in which it has not been able completely to clean out of its valley the gravels of the later glacial period, one can get an idea of the relatively long time separating the two periods.

B. Differences in weathering of the two moraines and their associated wash-plains. The great difference in age of the two glacial advances is further shown by the difference in the amount of weathering of their deposits. The later moraine, as seen in cuttings, is everywhere fresh and unweathered. The large stretch of older moraine north of Lake Creek does not show sections which will enable one to make a comparison with the later drift. The western of the two occurrences south of Lake Creek, however, shows a long section where the moraine is crossed by an irrigating flume. The moraine here is thoroughly disintegrated, bowlders crumbling to pieces beneath the blow of a hammer, while the same rock on the inside of the younger moraine is quite fresh. It may be noted, though, in this connection, that in one or two exceptional cases the younger moraine contains frequent decomposed bowlders.

It is, however, when we come to examine the gravels associated with the two moraines that the difference in amount of weathering is most apparent, and numerous placer openings and trial shafts in the gravels have made this comparison easy. Sections in the gravels in the gorge show that the bowlders are, with very few exceptions, perfectly sound. Numerous sections in the upper gravels show a large proportion of the bowlders to be thoroughly rotten. One of the most easily recognized rocks of the region is a coarse porphyritic granite. In the gorge gravels, bowlders of this rock are fresh. In the upper terraces they can often be picked apart with the knife-blade, and frequently have been cut across in digging the shaft, it being easier to cut across than to dig out blocks lying in the wall of the shaft. This very general and thorough weathering of the upper gravels, compared with the freshness of the gorge gravels, indicates that the former are several times older than the latter, and that interglacial was longer than postglacial time.

C. Differences in topographic expression and in amount of stream-dissection of the two moraines and their associated gravels. In a later place this consideration will be presented more fully. It is enough here to say that the younger moraine is the steeper and more rugged of the two. The differing amount of dissection is especially well brought out in the two gravels. Of course, the gorge gravels have been in large part cleaned out by the Arkansas in postglacial time, since along the main river conditions have favored erosion. More striking is the great amount of destruction of the upper gravels at points where erosion has not been favored. They have been completely cleared away by Lake Creek at its mouth, and by the small stream entering the Arkansas at Hayden. Between these two points no permanent streams enter the Arkansas from the west, but several dry valleys head in the old moraine, cross the wash-plain and enter the main river. Near the river they are in granite and narrow, farther back they are in gravel and widely open. These widely open valleys in the old gravels contrast well with valleys cut by much larger streams in the younger drift—as, for example, the valley of Lake Creek where it crosses the moraine—and point to the gravels being much older. There is reason to believe that the streams entering the Arkansas from the west between Lake Creek and Clear Creek have, by widening their valleys until they joined, succeeded in reducing the whole level of the upper gravel deposits some distance below its original height. The dry valleys which cross the gravel terrace north of Lake Creek head, as has been mentioned, in the older moraine. Their continuation from the river with essentially unchanged dimensions and expression, back across the gravel terrace into the older moraine, but not into the younger moraine, shows the connection of the older moraine and the higher gravels. The younger moraine is not eroded by any drainage originating on the moraine itself.

The relation of the moraine to the gravels shows that the valley of Lake Creek was at two distinct periods in Pleistocene time occupied by a glacier, and that these two periods were separated by time enough for the cutting of the rock-gorge of the Arkansas. And the much greater weathering and erosion of the older deposits indicate that interglacial time was much longer than postglacial time, in this region.

2. *The earlier moraine.*—The character of the older drift is well shown outside the younger moraine north of Lake Creek. Here, toward the south, it forms a low terrace several hundred feet wide rising some 30 to 50 feet above the wash-plain which fronts it. From a distance it looks almost like a second terrace rising above the general level of the upper terrace, but its surface is rolling and uneven. It is usually separated from the younger moraine by a shallow valley. Its surafce, while rolling, is less uneven and rocky than that of the younger drift; scattered erratics up to 6 or 8 feet in length are common over its surface, but these do not reach the size of those on the other moraine. Northwest, this terrace widens to about a mile, forming a gentle slope away from the later moraine to the wash-plain nearer the river. This older drift has not been traced beyond the Twin Lakes–Hayden road.

The older drift is mapped at two places south of Lake Creek. The western of these two occurrences (Fig. 1, 4) is not large enough to be of topographic importance. The other (Fig. 1, 3) is a low ridge nearer the river, apparently connected with a fragment of the upper terrace gravels, and less rugged than the younger drift just north of it. It is not in as marked contrast with the younger drift as the belt of older moraine north of Lake Creek, and there might be some doubt as to its identification. No sections occur, so that one kind of evidence as to its age is lacking.

3. *The later moraine.*—The later moraine forms a loop about the lower end of Lake Creek, with its higher parts, near the Sawatch Range, rising some 1,000 feet above Lake Creek. Its surface has already been described as more rugged than that of the older moraine, yet it shows typical kettle topography at but one place, where the Hayden road crosses the north lateral (Fig. 1, 1). The outer slope is the steeper of the two. An interesting feature of the inner slope of the north moraine is a series of ridgings which remain parallel to the main crest of the moraine for some two miles as it drops to the east, and which seem to represent later stages of accumulation during the beginning of the retreat of the glacier.

At several points there are sags in the moraine crest, and here the moraine is pushed forward as if tongues of ice had pushed out a short distance beyond the general front of the glacier. The best illustration of this is at the lower end of Lake Creek, where the main morainic ridge is breached, and a small moraine pushes out through the breach nearly to the Arkansas River. The contrast is especially noticeable on the north, where the two make a sharp angle with each other. A second illustration occurs on the north lateral, where it is crossed by the Hayden road, and again on the south lateral between the two areas of older drift.

Moraines of recession occur along the course of Lake Creek. The first of these is just below the lower lake—a belt of low morainic knolls which swings around and unites with the inner side of the main moraine. This moraine of recession can be traced to its union with the main moraine, but it cannot be separated from the main moraine thereafter. A second low recessional moraine swings in a semi-circle across the valley at Interlaken, separating the two Twin Lakes from each other. This has its wash-plain, and merges with the larger moraine, though it can be followed back as a distinct ridge for a greater distance than the moraine below the lower lake. A third morainic ridge (Fig. 1, 2), a part of a recessional moraine, is developed on the south side, just down-stream from the one just mentioned at Interlaken. It runs below the level of the lower lake, and is not found on the north side of the lakes. Masses of morainic drift occur within the rock-gorge, but irregularly distributed, rather than in the crescentic shape characteristic of recessional moraines. In all cases these moraines are small, forming a belt of rolling drift 20 to 30 feet high and not exceeding several hundred feet in width.

Above Twin Lakes village, in the rock-gorge of Lake Creek, the drift occurs irregularly and is not aggregated into moraines. Erosion and not deposition was here the rule. From the base of the mountains to the Arkansas the drift occurs in simple morainic embankments. There is an intermediate area, on both north and south sides, where an intermediate relation holds. On the south side of Lake Creek the south lateral rests against the lower slope of Lost Canyon Mountain, its crest dropping slowly to the east and interrupted only where cut by streams flowing into Lake Creek. At these places a typical moraine section is shown, as the moraine was built across the mouths of the lateral valleys which were occupied by streams in their lower course and entered the main valley well below the level of the glacier surface. Opposite the intervening divides the moraine crest is continuous with the crest opposite the valleys where it has not been cut away. Sections on the inner face of the moraine opposite the divides, however, frequently show rock in place; and while this inner slope is drift-covered, it appears that the drift forms but a veneer over the truncated spurs of the rock divides between adjacent lateral valleys, so that the apparently simple moraine along the base of Lost Canyon Mountain is really a cut-and-fill affair, moraine-veneered truncated spurs opposite the divides, and typical moraine embankments opposite the lateral valleys. This double character holds for four miles along the south side of the valley, and for a short distance along the north side back of Twin Lakes village.

4. *The Clear Creek morainic system.*—This paper is concerned with the Lake Creek region, yet it is permissible to note that the history which has been outlined above for the glacier occupying the valley of Lake Creek was duplicated in every essential feature by the

glacier occupying the valley of Clear Creek, four miles to the south. Here are two series of moraines. An inner one of late date is represented by two great lateral embankments rising 1,000 feet above the valley bottom of Clear Creek and extending to the Arkansas. These laterals do not unite toward the valley, but the lower moraines of the same age between them are connected with gravels which follow down the gorge of the Arkansas at levels not far above the river. Outside the younger moraines there are, both north and south, extensive areas of older moraine, better developed even than about Lake Creek, and associated with higher gravels which lie above and outside of the Arkansas gorge, and indeed are continuous with the higher gravels about Lake Creek. The same differences in expression, in weathering, and in dissection by streams hold here between the earlier and later moraines and gravels as in the valley of Lake Creek, and make less probable any serious mistake in the interpretation which has been given to the features of that basin.

II. PLEISTOCENE HISTORY OF THE UPPER ARKANSAS

1. *The terraces of the earlier glacial period.*— One of the most striking geological features of the Arkansas Valley is the great development of the high-level gravels. From Granite, for a distance of 10 miles to the north, they occur nearly continuously on the west side of the river. Opposite Hayden, on the east side of the river, the graded rock-plain which has been noted as occurring to the south, becomes covered by an extensive alluvial fan similar in physical composition to the gravel terraces west of the river, with its lower edge forming a terrace of the same altitude as the terrace on the west, but rising steadily from this height back toward the gulches which head in the Park Range back of Leadville. The earlier glacial period was a time of ice-erosion. The streams leading down from the glaciers were overloaded, aggrading was the rule, and extensive wash-plains were formed. In the Arkansas valley aggrading went on until the stream was flowing many feet, in some cases many scores of feet, above its earlier level. Wash-plains extended continuously along the main valley, and vast alluvial fans extended down from the glaciated mountain valleys on either side. About Leadville these fans are largely intact today; but on the west they do not seem to

have been so extensively developed, and are now found in distinct, but not conspicuous, remnants on the shoulders of Mount Massive between the glaciated valleys.

Emmons[1] and Hayden[2] have suggested that the gravels are lake deposits of an interglacial period. They do not seem to be interglacial deposits, as they are closely related to the earlier moraines; and interglacial time was an epoch of valley-cutting and not of valley-filling. But are the gravels lake deposits? To the writer there is nothing to suggest that they are not stream-built gravel-plains. The material is mainly coarse, bowlders up to one and two feet in diameter being very abundant. It is slightly or not at all stratified. Where coarse gravel and fine gravel alternate there is a rude stratification, but in the coarse gravel stratification is wanting. If the material had been deposited in a body of standing water, a marked development of foreset beds (delta structure) should be found throughout the gravels; but any such structure is lacking. At one point only was any considerable amount of fine material noted, just north of Cache Creek (Fig. 1, 5), at the base of Lost Canyon Mountain. Here there is a considerable body of fine gravel, and some clay, in the plain. This is explained by the protected position, between the points of discharge of Lake Creek and Clear Creek. It is probable that the more rapid building up of the plain both to the north and south may have left depressions which might be filled with finer material or even clay, but such deposits of fine material are very local.

Not only the character of the gravels, but the disposition of the surface, indicates stream-work. Emmons notes that south of Leadville the gravels occur on the spurs back from the river at an elevation 1,000 feet greater than along the river, and infers the elevation of the Park Range over the valley by that amount. But a similar rise of the gravels occurs west of the Arkansas, though the gravels do not reach the altitudes they do near Leadville. Gravel fragments occur on the foothills of Mount Elbert several hundred feet above the level of the terrace along the river. These gravel terraces rising toward the mountains have every appearance of alluvial fans. To the writer, who came into the region after several weeks in the Utah portion of the Great Basin, where the long slope of alluvial wash at the base of the mountain ranges is a striking feature, their topographic resemblance to alluvial fans was very strong.

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[1] Emmons, *Geology and Mining Industry of Leadville*, Second Annual Report, U. S. Geological Survey, pp. 220, 229.

[2] *Annual Report* for 1873, p. 53, and for 1874, p. 52.

The question may be raised as to the possibility of damming by the glaciers entering the Arkansas valley. The moraine of the earlier Lake glacier does not appear to have reached the present Arkansas by a half-mile, and cannot have dammed up the stream. Further the height of the gravels above and below Lake Creek is essentially the same. At Clear Creek the conditions are different. Here the old moraine lies along the western edge of the gorge, and the height of the gravels to the north seems to be determined by the rock-level at the top of the gorge outside of the moraine. The Arkansas was pushed to its present position on the east side of the valley by the advancing moraine of the Clear Creek glacier, and the height of the gravels up-stream determined by the position of that moraine. This does not necessarily mean, however, that a lake was formed to the north; the character of the gravels is against that interpretation. The probable explanation is that in earlier glacial time the advance of the Clear Creek glacier and moraine went on contemporaneously with aggradation by the Arkansas, until at the maximum the Arkansas was flowing on its flood-plain about the nose of the Clear Creek moraine, pushed to that position by the gradual advance of the glacier. Farther north also the Arkansas hugs the east side of its valley. This, however, is not due to pushing by glaciers, but probably to a greater supply of detritus coming in from the glaciated valley of Lake Creek, building a wash-plain with slope to the west, and constantly tending to push the main stream to the east.

2. *The work of interglacial time.*—Glacial periods are times of valley-clogging; interglacial periods, of valley-cutting. The first glacial period with its moraines and gravels was succeeded by an interglacial period in which the Arkansas and its tributaries were engaged in valley-cutting. To this period is assigned the excavation of the rock-gorge of the Arkansas. From a point two miles north of Lake Creek, south to beyond Granite, the Arkansas was flowing on the east side of its own gravel deposits and well to the east of its

earlier course. Here it quickly sunk its channel through the gravels into the underlying granite, and its interglacial valley is in consequence narrow and gorge-like. North of its rock-valley, toward Leadville, the Arkansas does not flow in rock, and its interglacial valley is much wider, averaging three-quarters of a mile, though not less deep than to the south. This difference in valley-width is, of course, due to the difference in hardness of the materials in which the valley has been opened. There is probably a double reason for the failure of the river to lay bare rock to the north. North of Lake Creek glaciers occurred on both sides of the valley, there was not the unsymmetrical development of wash that farther south forced the river to hug the east side of the valley, and it therefore kept more nearly its preglacial course. Further, the preglacial Arkansas was flowing in a graded rock valley which probably had a gentle gradient, while the interglacial gravels were laid down by rapid streams handling coarse material and building that same material into steeper slopes. Later erosion would naturally reach rock more generally along the lower course of the river where the gravels were less thick.

As the Arkansas cut its valley during interglacial time, the side streams were lowering theirs. Those from the east were flowing over a rock-graded plain thinly veneered with river gravel, and as they cut down, they dissected the plain and largely removed the gravel, so that now it occurs only in scattered bowlders over the divides between the tributary streams. The slope of these tributaries from the east steepens toward the main stream; they have not quite been able to keep up with the main stream in downward cutting. The small stream which enters the Arkansas through drift from the west at Hayden has swept away the whole terrace for a half-mile in width along its lower course, and at Lake Creek the terrace has been quite cleared away west of the river. No permanent streams enter the Arkansas between these two, but wet-weather streams originating on the old moraine and terrace have cut out wide, shallow valleys, whose depth is determined by the ledge of hard rock which the streams have found at the edge of the river. North of Lake Creek this action has cut out several broad, transverse valleys, but has not destroyed the original surface of the higher terrace. Between Lake Creek and Clear Creek there are different conditions. Here several streams come down the face of Lost Canyon Mountain, cross the plain, and enter the Arkansas. Only one of these, Cache Creek, is a permanent stream, but the others carry much more water than the channels which head in the moraine to the north of Lake Creek. The effect of their combined action is that the original surface has been cut into series of eastward-sloping terraces, whose level is determined by the distance the streams have cut into the rocky edge of the Arkansas gorge—levels which are lowest toward the south, where Cache Creek cuts deepest toward the river. These valleys have widened till they met, and in this manner the original constructional level of the terrace has been replaced by a terrace of stream-erosion. The only points where the original surface is kept are on the salients at the base of Lost Canyon Mountain, where the gravels have been protected from erosion by their position on the divide between the small valleys crossing the plain. Here the gravels rise to the level of the gravel fragments east of the river and north of Lake Creek. At one point nearer the river a remnant of the higher level is kept. A small hill just south of Lake Creek on the west side of the Arkansas rises 50 feet above the general level of the plain in its neighborhood. The part above the surrounding terrace-level is rock with a covering of gravel. This is a remnant, not of the original terrace, for it is covered with quartzite gravel derived from north of the Lake Creek region, but of an intermediate terrace which stood above the present terrace-level; and it is a witness to the general degradation of this part of the old plain. The Arkansas here cut across a shoulder of granite coming from the east, and this granite nucleus has preserved the gravel over it from removal.

The cutting of interglacial time was marked by the development of terraces (*F* in Fig. 3) at intermediate levels. The benches so produced are not conspicuous features of the topography, and are determined by the levels at which the streams came upon rock barriers as they cut through the gravels to the underlying rock. One such terrace is cut in the high gravels along the east side of the Arkansas opposite Hayden, and is determined by the highest rock-level in the gorge to the south. At this level in the gorge a narrow terrace is worked out in the rock. The gravel on these intermediate terraces is largely composed of quartzite bowlders of medium size, while the bowlders of the upper terrace are largely granitic in composition and contain only an insignificant amount of quartzite. Quartzite is abundant in the Park Range about Leadville, but is not found on either side of the valley about Lake and Clear Creeks. This difference in rock composition of the terrace gravels indicates that the upper gravels about Lake Creek were almost wholly composed of material swept in from the adjacent valleys, while during interglacial time the Arkansas was sweeping that material away and bringing large amounts of material down from the upper parts of the valley. Incidentally it means that in early interglacial time continuous gravel trains, above the level of the rock in the gorge, extended up towards the head of the valley.

3. *Second glacial and postglacial.*—The later glacial period marked a new advance of the ice, the accumulation of the younger moraines, and the development of a valley train in the rock-gorge of the Arkansas, but was not marked by any change in the course of the river. The later gravels occur in scattered terrace fragments north to Granite Gulch. North of that point they are not distinct. Postglacial time has been marked by the resumption of clearing by the stream, and the removal in large part of the terrace made during the later glacial advance.

III. GLACIAL EROSION

1. *Valley form.*—The cross-profile of a maturely glaciated mountain valley will be typically as shown in Fig. 4; a broad U-shaped valley below, surmounted by gentler, but still steep, slopes (*AB*) made by undercutting, which, in a region not too thoroughly glaciated, will pass above into the gentle slopes (*AC*) of preglacial origin. The most striking feature of a view along such a valley will be its broad U-trough. This form is well shown both in the main valley of Lake Creek and in those of its tributary valleys which were occupied by ice. The best illustration is afforded by the middle and upper part of Willis Gulch. No hanging valleys above, and no rock-sills or buttresses below, mar the simplicity of its general form. It is a remarkably regular example of the type. The middle part of several

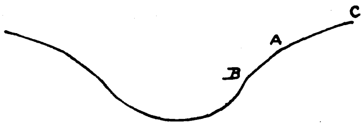

FIG. 4.—Cross-profile of a glaciated valley.

other tributaries which were occupied by valley glaciers show the same general features. See in this connection Fig. 10.

The main valley above Twin Lakes shows the same broad U-cross-section, but in the matter of broad detail there are serious interruptions to the regular profile, in rocky barriers across the stream-floor, and in some cases in buttresses standing out prominently from the valley side. The longitudinal profile of the valley is not even. For a distance the stream may be swinging from side to side in an alluvial valley floor, and then may for a fraction of a mile be flowing with more rapid fall in a rock-gorge between the low, rolling, glaciated hills of one of the valley-sills. Four such sills occur in the main valley within a distance of six miles above the mouth of the rock-gorge. The largest is the one at the mouth of the rock-gorge. It consists of a series of rounded rock-bosses rising to the higher walls of the valley on either side, but is most conspicuous on the north, where it forms a long rocky barrier, reaching nearly to the upper limit of glaciation. The difference in level of the stream between where it enters this rocky portion of its valley above, and where it leaves it below, is 600 feet; and it is here flowing for a mile in a narrow postglacial gorge. Other sills occur at several points upstream, but are not as conspicuous as the one at the mouth of the rock-valley.

Rock-bosses standing out from the valley wall also occur. The two on either side of Monitor Gulch are the best—Monitor Rock[1] on the west side, and another nearly as high on the east. Monitor Rock rises nearly 1,500 feet above the valley floor, nearly to the upper limit of valley glaciation, and stands out conspicuously into the valley.

An even U-trough is the ideal toward which the glacier tends to shape its bottom; but rock-sills and buttresses show that in the process of valley-cutting the glacial bottom may be fashioned quite irregularly, on account of differences either in rock-resistance or in glacial erosion at different points. Monitor Rock may be due to difference in rock hardness, as it is composed in part of a finer grained, denser, and probably more resistant facies of the porphyritic granite which is the common rock of the valley. But it is not possible to make any general statement as to the greater hardness of the rock barriers, because much the same kind of rock is found all along the valley. In the present case these irregularities occur well below the limit of hanging valleys, and so in that part of the valley excavated by the glacier; they are not due to subaërial erosion, though the prominence of projecting buttresses may have been so increased.

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[1] Described by Hayden, *Annual Report* for 1873, p. 54.

The separation of the different elements of the valley side indicated in Fig. 4 is difficult, on account of weathering and of the indefiniteness of the upper limit of glaciation. The upper preglacial slope is easily recognized in the rounded summits of the divides between the tributaries to Lake Creek. It is a graded slope of about 10°, is usually grassed over, and is shown where the divides between the tributaries have not been sharpened by glacial erosion. But it is not easy to distinguish the cliff of glacial abrasion from the oversteepened cliff above the former glacial bed. The glaciated valley surfaces have been largely destroyed by subsequent weathering, and where the height of the glacier was changing, it may easily have been that the passage from a well-glaciated wall below to a non-glaciated wall above was originally gradual and indefinite. In the lateral valleys weathering has practically destroyed all the glacially smoothed surface of the valley walls, and the upper limit of glacial erosion can be made out only approximately. In the main valley the upper limit can be more definitely fixed, and while even here there is doubt about its exact location, a lower portion of the valley wall can be recognized, showing under favoring conditions well-developed glaciated surfaces, while an upper, steep, rocky portion

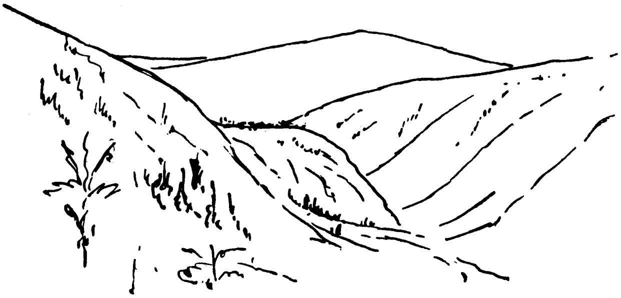

FIG. 5.—Monitor Rock, Lake Creek Gorge, looking down the gorge.

seems to have been above the ice-level, and to have been formed by undercutting, or sapping, of that part of the valley side above the glacier surface. The ridges between some of the more vigorous lateral valleys, as between Crystal Lake and Willis gulches, seems to show this intermediate slope due to glacial sapping. The preglacial slope has been destroyed by valley-cutting, but the steep slope of the upper glaciated valley gives place to a gentler, but still steep, slope, which is best explained by glacial sapping. The same element in the valley slope is shown in the upper angle of the truncated spur in the main valley shown in Fig. 9.

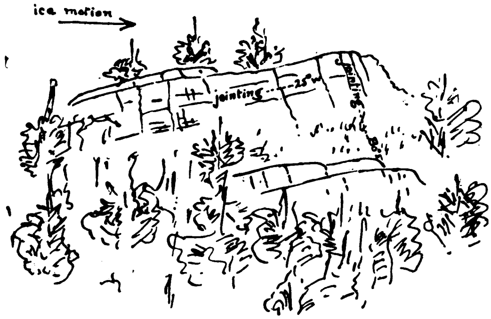

FIG. 6.—Glaciated and jointed ledge.

2. *Glaciated surfaces.*—Glacially smoothed surfaces are common in the main valley, especially so on the rock-barriers and rock-bosses which were peculiarly exposed to glacial erosion. In the matter of abundance of glaciated surfaces there is a great difference between the main valley and its tributaries. The larger lateral valleys, such as Willis Gulch and Crystal Lake Gulch, have suffered an almost complete destruction of their glacial surfaces. At one point on the wall of Willis, glacial smoothing was recognized, and in Crystal Lake Gulch a small area on the west wall, and a certain amount of smoothing on the hummocky surface of the cirque floors, are all. Some of the other gulches show even less remnants of glacial surfaces than do these two. Glacial striæ are found only on the more perfectly preserved surfaces in the granite of the main valley.

A matter of importance is the proportional amount of erosion due to glacial abrasion or glacial plucking. In almost all cases rock-ledges and rock-bosses show a great difference between the stoss and lee ends. The former are apt to be well-rounded; the latter, almost invariably steep and coarse-hackly. The jointed structure of the granite in the main valley is such as to favor plucking. The accompanying figure (Fig. 6) of a glaciated ledge on the north side of the valley brings this out. Three prominent series of joints intersect the granite. The direction of ice-movement is toward the east. One series of joints has a dip of 70° E., and so runs almost at right angles to the direction of ice-movement, and gives easy conditions for plucking. Two other series of joints dip respectively steeply to the south and more gently to the north, while the blocks into which they divide the rocks pitch to the west. The result on the form of the ledge is shown in the figure in which the glaciated surface rises to the east, evidently determined by the jointing. When a ledge cut out from a rock jointed in this manner is seen end on, it usually shows a composite profile and not a simple glaciated curve, the profile being clearly controlled by the jointing. The connection between jointing and glaciated surface in such instances means that plucking has played a large part in glacial erosion over the surface, as well as on the lee side of the boss and that a process of pluck and heal has been going on, the ice breaking out great blocks along planes determined by jointing, and then rounding off the broken edges by glacial abrasion. This form of ledge surface is not a matter of occasional outcrops; in the middle part of the valley the whole valley sides for a distance of hundreds of feet vertically, and for considerable distances along the valley, shows this intimate relation between joints and form of the rock outcrops. On the south side of the valley, on both sides of Crystal Lake Gulch, glaciated rock outcrops (Fig. 7.) rise from the stream to the upper limit of glaciation, and all show glaciated stoss sides rising at an angle of 30° toward the east, and ending in a lee slope plunging steeply to the east. The two structures are determined by the line of jointing in the granite. Farther up the valley,

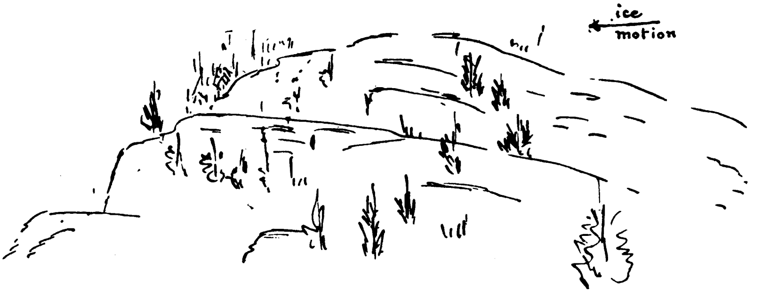

FIG. 7.—Glaciated ledges on south side of Lake Creek.

near Everett, an extensive area of glaciated ledges on the south side of the valley shows the ledges sloping to the east—again an expression of rock-jointing, which in this case holds a different direction from that farther down-stream. Facts of this kind, occurring through the valley, point to glacial plucking as being as important as, perhaps much more important than, glacial abrasion in the erosion of Lake Creek valley.

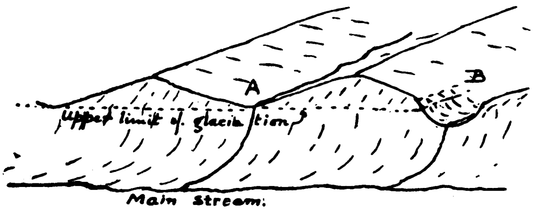

FIG. 8.—Diagram of hanging valley.

Other minor features of glacial smoothing are illustrated at different points in the main valley. Evenly rounded ledges of considerable size, shallow saucer-shaped (in cross-section) furrows, glacial undercutting, and in some cases a smoothing of parts of the protected lee sides of eminences, also occur. A feature noticed in one or two cases was the production of nearly flat, smoothed surfaces intersecting at a small angle, and separated by a sharp ridge, the whole being worked out of sound rock. Evidently some change in the current of the ice had taken place at that point. Of similar nature is the gouging of a flat surface by a shallow groove, much as a shallow groove might be cut in a planed board by a gouge of large curve.

3. *Hanging valleys and truncated spurs.*—When the main valley of a preglacial drainage system has been deepened by glacial erosion, the relations which should exist after the disappearance of the ice may be represented by Fig. 8. The spurs of the old divides and the lower ends of the tributary valleys have been cut away, giving hanging valleys and truncated spurs. It is not essential that the upper limit of glaciation should coincide with the level of the lateral valley, as it does in this figure. The tributary valleys may or may not have been occupied by glaciers. If they have been so occupied, the form of the hanging valley will be like *B* in the figure, broad and U-shaped; if not, like *A*, more or less broadly V-shaped, according to the steepness of the preglacial valley. Terminal facets marking truncated spurs, and both glaciated and non-glaciated hanging valleys, are found along the sides of the Lake Creek valley.

One of the best illustrations of terminal facets separating non-glaciated hanging valleys occurs just above the mouth of the gorge on the south side of the valley. The ice here reduced the valley side to an even curve leaving the wall not at all broken by rock buttresses. In this manner a series of triangular facets was formed against the divides between short tributary valleys, which right here were not occupied by glaciers. Subsequently interglacial and postglacial erosion have cut these valleys further toward the main valley floor, and have furrowed the facet faces, but they still distinctly show their faceted character. The facet shows steeper in the lower three-fourths of its face, a gentler, but still steep slope, above to the apex of the facet. In Fig. 9 the dotted line *AB* marks the upper limit of glaciation; the part of the facet below that line seems to represent glacial abrasion, the upper part the work of glacial sapping. The truncated spurs along the base of Lost Canyon Mountain have already been mentioned (p. 292) while speaking of the moraine.

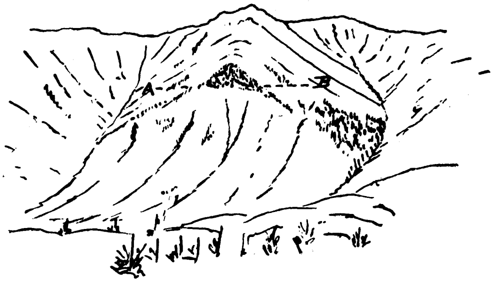

FIG. 9.—Truncated spur on the south wall of Lake Creek Valley.

Hanging valleys and truncated spurs obviously go together, and hanging valleys are a characteristic feature along Lake Creek. Some of these hanging valleys were occupied by glaciers, some not. Crystal Lake Gulch, La Plata Gulch, and La Plata Basin are glaciated hanging valleys. Willis and Boswell gulches to the east were glaciated valleys, but are not hanging valleys, as the main glacier did not cut below the level of the tributary valleys in this lower part of its course. Of the three mentioned, that of Crystal Lake Gulch is most characteristic. Fig. 10 shows this hanging valley as seen from the opposite side of the main valley. It is a broadly opened U-valley, ending on the side of the main valley about 1,000 feet above Lake Creek. La Plata Basin and La Plata Gulch, the two tributary valleys from the south, next west of Crystal Lake Gulch, and Hayden Gulch, entering from the north opposite Crystal Lake Gulch, are hanging valleys of similar type. The other tributary valleys which enter Lake Creek above Twin Lakes are either short V-valleys, unoccupied by glaciers, or occupied only by masses of ice forming cirques at their head, or else are, like Echo Gulch, U-valleys in their middle and upper course, and V-valleys below, the ice-tongue not having reached the main valley.

4. *Two periods of glacial erosion in the gorge.*—The moraines of the Twin Lakes glacier show two glacial periods separated by a long interglacial period, during which the cutting of the rock-gorge of the Arkansas took place. Only portions of the earlier moraine remain, but they show that certainly in part, and probably on the whole, the earlier glacier reached farther into the valley than did the later glacier. The gravels associated with this earlier moraine are much greater in bulk than those associated with the later moraine. The material of the moraine was obviously derived from the valley of Lake Creek, and the great abundance, in the gravels, of material derived from the valley of Lake Creek indicates that the gravels

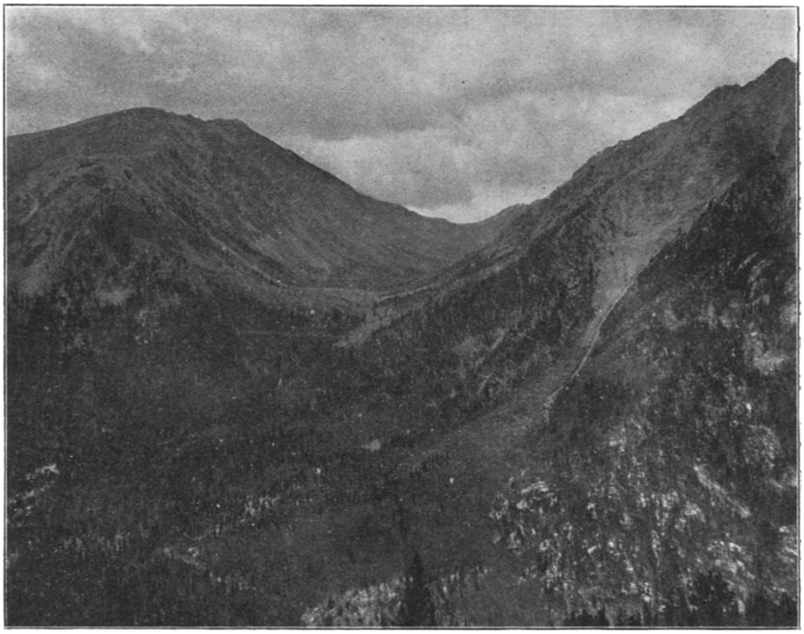

FIG. 10.—Hanging valley of Crystal Lake Gulch.

were largely from this same area. These things suggest strongly that the material removed from the valley during the earlier period of glaciation was as great, and probably greater, in amount than that removed during the later glaciation. The question naturally rises: Is it possible to detect in the rock valley of Lake Creek evidence of these two glaciations, which we know must have occurred? It is not easy, since the work of the later period would continue that of the earlier, and all products of erosion would be removed from the valley. But it is thought that evidence in favor of two periods of glacial erosion, with the larger amount of work done in the earlier period, is found in the relation of the hanging valleys to the main valley.

In typical hanging valleys the contours of the lower slopes of the main valley continue unchanged beneath the hanging valley. A cross-section of the main valley and long profile of the lateral hanging valley is given in Fig. 11, in which *AB* is the longitudinal profile of the hanging valley. But the profile of the typical hanging valley of the Twin Lakes region would be represented by *AECD*, the triangle *ECB* representing a narrower or broader notch which has been cut out from the side of the general valley immediately below the hanging valley. Such a re-entrant could conceivably be cut out by the main glacier, or by the lateral stream. There seems to be no good reason why the ice should favor the side wall beneath the hanging valleys generally, and in some cases these cuts are too sharply re-entrant for ice-work. Further, these notches contain in almost all cases morainic material; and this is the case whether the lateral valleys were occupied by ice or not. They are areas of glacial deposit rather than of erosion. Their origin seems to be as follows: During the earlier period of glaciation the main glacier cut its valleys below the level of the tributary valleys, producing normal hanging valleys, the longer of which were occupied by tributary

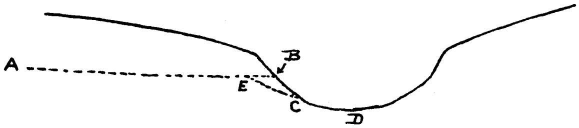

FIG. 11.—Profile of hanging valley.

glaciers and became U-valleys, the shorter being hanging V-valleys. During the succeeding interglacial period the tributary streams cut back the mouths of their hanging valleys for a greater or less distance, forming V-valleys or ravines at the lower end of the U-valleys, and deepening the V at the lower end when the valley had not been previously glaciated. The glacier of the second period smoothed the walls of these interglacial stream-cut re-entrants where they were not too sharp, but in practically all cases dumped more or less morainic material into them. Postglacial time has enabled the streams for the most part to cut through this drift, and below the mouth of the hanging valley they follow a steeper course, chiefly in morainic débris, but occasionally cutting into the solid rock. This interpretation of the phenomena at the mouths of the hanging valleys implies that the larger features of the forms of the glacial valleys were assumed in earlier glacial time—an inference in accord with the evidence of the moraines.

POSTGLACIAL CHANGES

Since the final disappearance of the ice, many changes of minor importance have taken place, in the way of both erosion and deposition. Streams flowing across drift and across rock barriers in the valley of Lake Creek have cut their channels. Behind the recessional moraines of Lake Creek considerable deposition has taken place, forming the extensive meadow at the head of Upper Twin Lake, and smaller patches of bottom-land further up-stream. The most conspicuous changes, however, are the rock-weathering and landslides along the main valley of Lake Creek, but especially along and at the head of its tributary valleys. The almost entire destruction of glacially smoothed surfaces in the tributary valleys has been mentioned. Here, at altitudes near and above the timber line, there has been a steady rain of rock fragments from the valley sides, and talus cones are everywhere present, mantling the lower parts of the gulch walls, and in many cases merging to make a nearly continuous talus slope. In addition to this gradual accumulation of fallen blocks to make a talus slope, great masses of broken rock have fallen from the sides and shot out to or beyond the axis of the valley. In one case, in the upper end of Willis Gulch, for a distance of half a mile along the valley side, and for a height of 1,000 to 1,500 feet above the valley bottom, the rock along the side of the gulch has slipped down and out in a series of lobes whose festooned and ridged surfaces express the flow within the mass of the landslide. In a number of instances landslides have dammed up the streams and caused small lakes; indeed, the small lakes in the gulches are almost uniformly formed in this way, and lakes occupying rock basins are rare.

MOUNTAIN FORM

Mountain form is an expression of two factors: rock structure, including original form and internal arrangement, and erosive processes. So far as the first of the two factors is concerned, conditions in the Twin Lakes region are simple. The rocks are all completely crystalline, and are granite, granite porphyries, and granitic gneisses. Their composition is such that no great difference may be expected in resistance to weathering, and their surface distribution bears this out, for they appear to be largely independent of topography. The porphyritic granite has already been referred to as one of the rocks most characteristic of the valley of Lake Creek, and it is possible that its somewhat greater capacity for weathering may have determined the course of the preglacial Lake Creek; but the ridges which separate the valleys tributary to Lake Creek are in places porphyritic granite, in places gneiss, and the difference in the rock seems to make but little difference in the character of the divides. In some instances the jointing of the rock plays a part in shaping minor details of form, the rough serrate ridges about La Plata being worked out on a jointed compact gneiss which holds its form well and gives the peculiarly jagged outlines to the lower divides; but petrographically the Twin Lakes area is a granitic complex, and differences in form are to be explained by differences in the character of the erosive processes.

The erosive processes which have been at work in the area are two, stream-erosion and glacial erosion. The larger features of the region were worked out by streams in preglacial time. These larger features were profoundly modified in places by ice-erosion in Pleistocene time.

The preglacial topography of the Arkansas valley and of the adjacent Park and Sawatch ranges can only be inferred from those portions of the region which were not subject to glacier-erosion during the Pleistocene, and have thus retained their preglacial form essentially unchanged to the present. The character of this topography was suggested in the opening pages of this paper. Briefly it was as follows: the Arkansas was flowing in a broadly opened graded valley between ranges which rose on either side to a height of from 3,000 to 5,000 feet, but which were characterized by relatively gentle and graded slopes. The term most applicable to such mountains is "massive." A view of Lost Canyon Mountain (Fig. 14) from the Arkansas valley is probably typical for the mountain range in general in preglacial time.

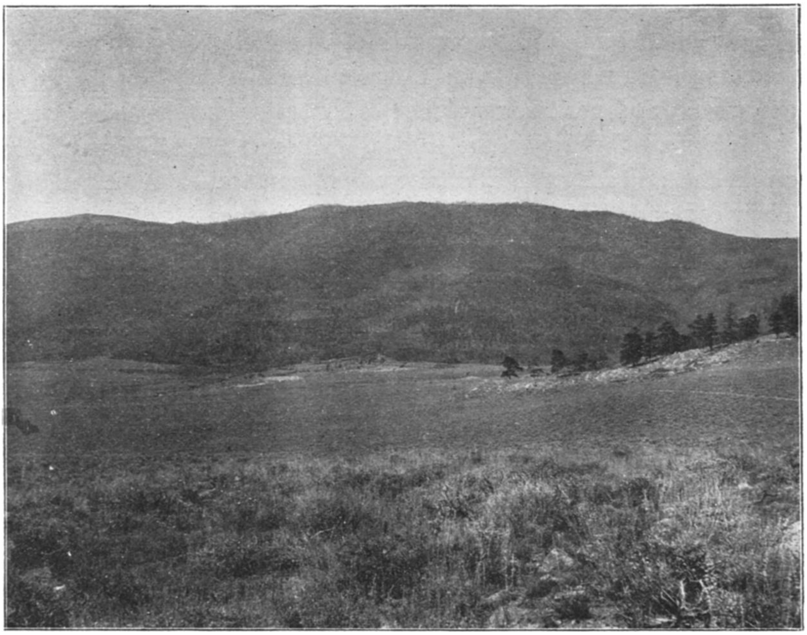

FIG. 12.—Lost Canyon Mountain from the Arkansas Valley.

The study of mountain form about Twin Lakes is the question how far in any particular locality this preglacial type of mountain has been destroyed by glacial erosion; how far cliffs, arrêtes, and peaks of glacial origin have replaced the more gentle and even slopes of mature subaërial erosion. Back toward the divide of the Sawatch

Range, where the head-feeding valleys of the glacial streams were working against each other, cirque action was general, sharp forms prevail, and the general view looking west toward the divide from any high point near the Arkansas shows a sea of sharp peaks. The multiplication of tributaries back in the range leaves scarcely any part untouched by glacial action. Fig. 14 is a view taken looking across Lake Creek toward La Plata Peak (14,342 feet), and shows something of the character of the area where little preglacial surface is left, the ridge in the foreground on the right being the only preglacial surface in the view which shows. About Twin Lakes, and nearer the border of the valley, there are considerable areas in which the two types of topography resulting from the two agencies occur together, since here the drainage of the tributaries of the Arkansas is concentrated in trunk channels of their lower course. The general form of Lost Canyon Mountain as seen from the Arkansas valley has been mentioned. Fig. 13 shows the evenly rounded summit of pre-

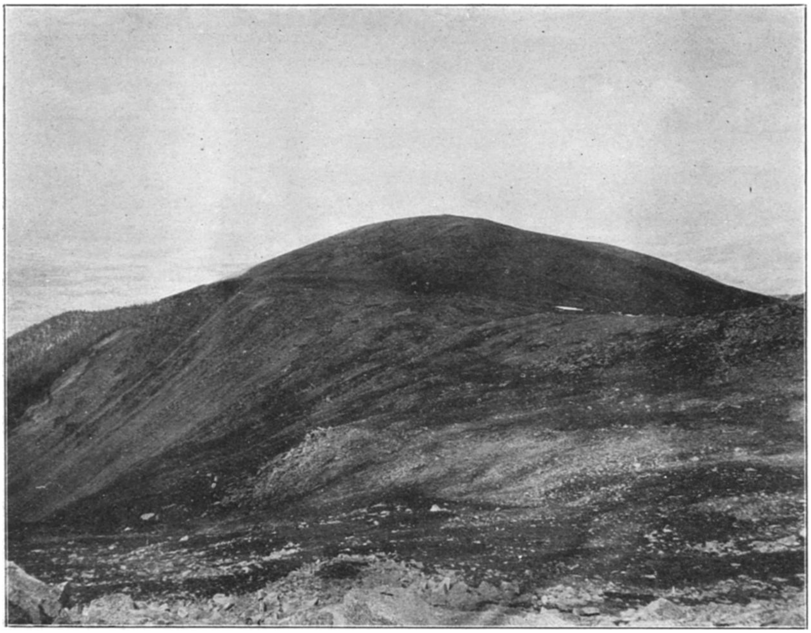

FIG. 13—Summit of Lost Canyon Mountain, with the upper edge of Boswell Gulch cirque on left.

glacial date at a height of 12,800 feet above sea-level. The steep slope on the left is the upper edge of Boswell Gulch amphitheater, and is of glacial origin, and the view shows the manner in which cirque-action was gnawing into the preglacial topography at the close of the last glacial period.

In using the present topography of the non-glaciated areas about the Upper Arkansas to illustrate the preglacial topography, it is assumed that substantially no change has taken place in those areas since the commencement of glacial time. Strictly this is not true, as these areas were subjected to subaërial erosion during Pleistocene and post-Pleistocene times; but it is not believed that the kind of changes then going on was different from the changes of preglacial time. Nor does it seem probable that the amount of change which has taken place since the commencement of the Pleistocene would be great for an area which had then reached maturity under atmospheric and stream agencies.

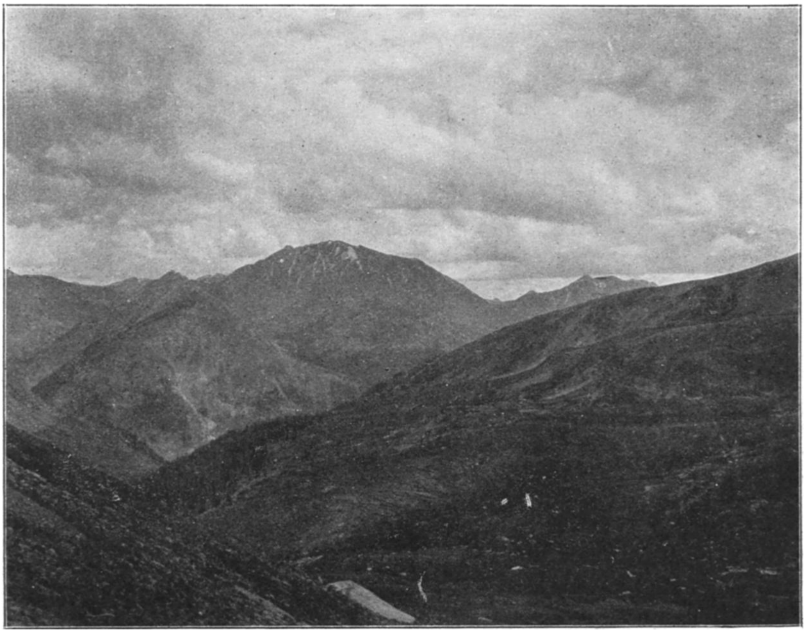

FIG. 14.—La Plata Peak from the north side of Lake Creek.